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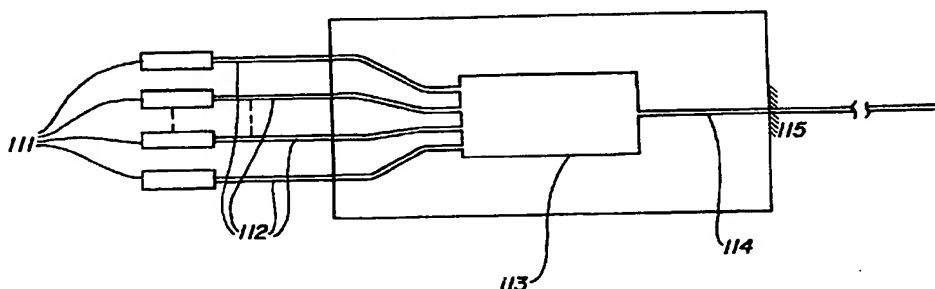
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(54) Compound laser system for high power density

(57) The present invention provides compound laser system for generating beams of high brightness and high power density by constructive phase coherent combination of the beams generated by a number of individual sources of coherent radiation. In one preferred embodiment, it provides a system for the delivery of high powered output from a set of inexpensive, comparatively low-powered diode lasers and comprises three subsystems: a diode laser subsystem which is the source of power for the system; a combiner subsystem which combines the output of the diode lasers; and, an optional delivery subsystem which may be needed to deliver the combined output to its desired destination for industrial or medical applications.

The combiner subsystem may be implemented in its entirety as an Integrated Optical Combiner, a single component, performing all the combiner subsystem's functions. Different preferred embodiments of Phase Coherent Integrated Optical Combiners are proposed. One of them employs an optical fiber having a shaped core to provide efficient matching to the geometry of typical laser diodes. Each diode laser's output of a diode laser array is captured by a single optical fiber with a core whose cross-sectional shape is contoured so that major and minor axes of a laser diode's output shape are not larger than major and minor axes of an optical waveguide and whose numerical apertures are closely matched to the numerical apertures in the directions of corresponding axes.

FIG.11



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Description

The present invention relates to lasers and optoelectronics and in particular to new compound optical sources of coherent radiation for generation of high power densities based on summation of the power of few separate laser components by an optical beam combiner. The laser system may be used for combination of beams irradiated by multiple diode lasers or a diode laser array employing beam combining components based on specially configured optical fiber and integrated optical waveguide system to pump optical fiber amplifiers or active crystals in miniature solid state lasers.

For many industrial and medical uses, the key attribute of a laser system is the power density that can be delivered to a particular site or point. Another desirable aspect of power delivery systems is that the laser's output be delivered to points remote from the laser and without being limited by the laser's physical orientation. Employing inexpensive semiconductor diode lasers instead of standard lasers is preferable for many industrial applications, since these lasers offer simple alignment and can easily be substituted for service or repair, if required. For example, such diode lasers could replace conventional laser sources for welding, cutting and surface treatment or can be used for pumping miniature solid state lasers and optical fiber lasers or amplifiers. The power needed for these applications, however, exceeds the power available from single low-cost diode lasers and has therefore required the use of high cost, high output lasers. Because the targeted applications require power that exceeds that of a single diode laser, one can use an array of diode lasers whose individual beams should be combined by some optical system and then coupled into an active optical fiber or an active crystal.

Such diode lasers, typically rated around 1 W, exhibit output cross sections of 200 μm by 1-2 μm and divergences of 20° and 40° in the respective cross-sectional major and minor axes. The outputs of these individual diode lasers are combined in the present state of the art by capturing each diode laser's output with a standard round optical fiber. The diameter of the core of the individual fibers is chosen such that it will encompass or cover a diode laser's largest output dimension, e.g., in the case of a 200 μm by 1-2 μm output pattern the capturing fiber's core diameter will be 200 μm ; with a typical thin cladding this would be at least a 220 μm clad fiber. Typically cylindrical lenses are affixed to the diode lasers or to the end of the individual receiving fibers to reduce beam divergence. Groups of these individual fibers are then combined by being bound together, and packaged in a launch connector.

All optical systems have an inherent phase volume stated by Streibel's invariant, which for circular cross sections is $d^2 \eta \sin \Theta$, where d is the beam diameter, Θ is the angle of the beam transverse divergence and η is refractive index of the medium. Brightness of the beam

is proportional to this invariant and can be increased only by increasing the beam power. The beam power density, however, is inversely proportional to the beam cross section, so an increase in the cross section yields a significant decrease in power density. Since the phase volume cannot be decreased by an optical system, the goal of power delivery systems should be to improve in brightness at the output of the system and the increase in beam power by minimizing loss in the system, particularly at system junctions, or the increase in power density by decreasing the beam cross section.

Present systems significantly decrease brightness of a diode laser's output at the coupling between each individual diode laser and optical fiber capturing the diode laser's beam. This is due to the difference in cross-sectional area dictated by the cross-sectional shape and the difference in numerical apertures of the laser and fiber. The diode laser has rectangular-shaped output and different numerical apertures in the directions of both principal axis of the rectangular cross section. The optical fiber used as the receiver has a circular cross-section, with a diameter approximately equal to the longer rectangular axis of the laser's output and matches numerical aperture of the laser only in this direction. Another loss of power and decrease of brightness occurs at the junction between the bundled, individual fibers coming from individual diode lasers and the single standard circular cross-sectional fiber into which the collected output is sent.

Figure 1 shows the prior art, where a high loss interface 5 occurs between diode lasers 2 and combiner subsystem 6 of round fibers 4, and a second loss interface 8 occurs where the combiner subsystem's output 11 is sent into a receiving port 29 of delivery subsystem 12 having a diameter similar to that of the bundled output. At each of these interfaces the power density decreases due to losses and the increase in cross-sectional area of the receiving fibers. Fiber 13 carries the total captured output of the diode laser array and is considered the deliverable output of the system.

Current art is focused on the problem of minimizing the power loss at the high loss-prone junction between an optical device such as a diode laser and a single round optical fiber. The solutions used in current art focus on the creation of micro-lenses at the end of a round optical fiber to focus the light beam into the fiber, or the insertion of a lens between the source and the fiber to achieve the same purpose. Neither reduces the coupling losses at that junction. U.S. Patent 5,256,851 describes the use of an asymmetric hyperbolic micro lenses on a single mode optical fiber to enhance the coupling efficiency of a diode and a fiber by matching the ellipsoidal ratios of the laser diode and the lens. This improves upon earlier microlenses described in U.S. Patents 5,011,254 and 4,932,989. U.S. Patent 5,127,068 teaches how to couple the light from an array of laser diodes into a plurality of bundled optical fibers using a cylindrical microlens made from a small diameter multimode optical fiber. U.S. Patent 4,723,257

describes a laser diode pumped solid state laser comprising an optical fiber transmitting pumping radiation. These approaches are not practical, however, when the output of the diode laser has axial ratios larger than 10:1, as is typically encountered in high-power multimodal diode lasers. US Patents 4,818,062 and 4,688,884 describe an optical fiber having improved capability to receive light energy from a diode laser. The fiber has a tapered input end squashed into all elongated cross section to match both the diode laser numerical apertures and its cross section. The squashing of the fiber end can not, however, provide the ratio of the fiber cross dimensions as large as 1:20 required for effective matching to the diode laser. Even in this case the tapered section only serves as yet another optical means to input diode radiation into the final circularly symmetric fiber cross section. Moreover, tapering of the fiber from its elongated end to its round end changes rectangular configuration of the input laser beam which may be undesirable for certain applications. For example, typical diode laser array has irradiates 12 beams of rectangular cross section oriented along its horizontal plane of p-n junction. To recombine these beams in such a way that long axes of all the beams are oriented in the vertical direction one need flexible means to transmit a plurality of the beams without changing of brightness and shape of each of the beams. Therefore, for many practical applications, it is desirable to have means of efficient coupling of the light from diode lasers into optical fibers while preserving brightness and rectangular shape of the light beam irradiated by diode laser over whole the fiber length. To solve this problem a special beam combiner systems must be designed.

The effective beam combiner is also a key component of many compound laser systems based on constructive superposition of beams generated by a number of individual sources of coherent radiation such as diode or fiber lasers. For example, the output radiation power of semiconductor lasers can be increased, retaining the spatial coherence, by the use of all array of strip structures formed on the same substrate and coupled either directly by the tunnel effect or indirectly by intermediate stripe waveguides. Although the output power can be increased considerably in systems of this kind, the problem of cooling the substrate remains and it has not yet been solved satisfactorily.

In the case of a fiber laser, the output power of the fiber lasers is governed by the pump radiation power coupled into the active fiber material, i.e. it is also limited by the power and spatial coherence of the semiconductor laser usually employed as the pump source.

One technique to achieve high-power laser operation is to spatially separate subgroups of lasers and then coherently combine their outputs.

Corcoran C.J. and Rediker R.H. (Appl. Phys. Lett. 59, 759(1991)) have demonstrated a system of five diode gain elements, i.e. semiconductor diode lasers having one facet antireflection-coated, operated as a coherent ensemble by use of an external cavity control-

led by a spatial filter or a hologram. The gain elements spatially separated and fiber coupled into the cavity. Collection of the fibers with microlenses on their facets, bulk lenses and spatial filters formed the means for phase-coherent superposing of radiation from the separate lasers in the system.

The disadvantages of this system are the bulky design, i.e. the using of a separate optical elements such as lenses, filters, holograms. As a consequence, this reduces the efficiency of summation of output radiation and results in increasing of the threshold of the laser system generation. Moreover, in this system it is difficult to avoid parasitic feedback due to undesirable reflections. When a system of this kind is used, additional devices are needed to concentrate the radiation in a single-mode waveguide channel.

The above mentioned problems clearly hinder the penetration of laser diodes into markets requiring high laser powers or high brightness. The present invention removes these difficulties.

The objectives of the invention are as follows:

1. To provide a compound laser system having high brightness and high power density of the output beam by efficient combination of the beams generated by a number of individual sources of coherent radiation.
2. To provide a simple, compact and efficient beam combiner performing constructive superposition of the beams generated by individual laser sources.
3. To provide an efficient method for phase coherent constructive superposition of beams from individual sources by employing a common feedback for all these sources.
4. To optimize the coupling efficiency at the diode laser to optical fiber or optical waveguide junction and provide a means for preserving brightness of the beam over the waveguide length.
5. To create a diode laser delivery system which includes a diode laser subsystem, a combiner subsystem that transitions the multiple outputs of the diode lasers into a single output from an optical fiber or optical waveguide and a delivery subsystem.
6. To create multiple embodiments of the combiner subsystem, including all integrated Optical Combiner which is a discrete component containing the full functionality of the entire combiner subsystem or a subset.
7. To optimize the power transfer efficiency at the junction between the combined optical fibers or optical waveguides and the single power-delivery optical fiber.

The present invention provides compound laser system for generating beams of high brightness and high power density by constructive phase coherent combination of the beams generated by a number of individual sources of coherent radiation. It provides a

laser system comprising at least two lasers whose output beams are combined by a means for phase-coherent superposing and by a common feedback reflector. In particular, it provides a system for the delivery of high powered output from a set of inexpensive, comparatively low-powered diode lasers comprises three subsystems: a diode laser subsystem which is the source of power for the system; a combiner subsystem which combines the output of the diode lasers; and, an optional delivery subsystem which may be needed to deliver the combined output to its desired destination for industrial or medical applications. The combiner subsystem and the delivery subsystem may use optical fibers, a free-standing form of optical waveguide. These systems may also use captured waveguides. The term "waveguide" is used to cover both free-standing waveguides or optical fibers, and captured waveguides. If only a particular kind of waveguide is to be used, the description "optical fiber" for free-standing waveguides or "capture waveguide" will be used as needed.

The combiner subsystem may be implemented in its entirety as an Integrated Optical Combiner, a single component performing all the combiner subsystem's functions. Each diode laser's output is captured by a single waveguide having a core whose cross-sectional shape is contoured so that its major and minor axes are not less than those of the diode laser output's major and minor axes and having a means to closely match its numerical apertures to that of the laser in the directions of corresponding axes. This means of numerical apertures matching can comprise, for example, some micro-optics or shaping the fiber end faces to make a micro-lens directly on the fiber. The matching cross-sectional shape may also be achieved using a cluster of circular shaped optical fibers where the diameter of each fiber is approximately equal to the minor axis length and a number of such fibers used, side-by-side, is approximately equal to length-of-major-axis divided by the optical fiber diameter. The waveguides receiving the diode laser's output are called input ports into the combiner subsystem. Waveguides are combined in the combiner subsystem, which contains combiner elements that combine two or more waveguides into a single waveguide. These combiners are cascaded until there is a single waveguide. This single waveguide is the single combiner subsystem output, called the combiner subsystem output port, whose cross-sectional shape depends on the number and cross-sectional shape of the input ports. A delivery subsystem takes output from the combiner subsystem using a standard round or contoured optical fiber core, depending on the cross-sectional shape of the combiner subsystem's output.

The combiner subsystem minimizes the power loss at input port interface by the use of input ports whose major and minor axes dimensions closely match those of the diode laser's output. The combiner subsystem's output has a cross-sectional core shape whose major and minor axes dimensions depend on the number and shape of the input ports.

Power loss is minimized at the junction between the combiner subsystem and the delivery subsystem by using optical fiber in the delivery subsystem whose major and minor axes approximate the major and minor axes of the combiner subsystem's output port and whose numerical apertures approximates the numerical apertures of the combiner subsystem.

The above, and other objects, features and advantages of the present invention will become apparent from the following description read in conjunction with the accompanying drawings.

Figure 1 depicts an example of a present state of the art diode laser fiber optic system.

Figure 2 depicts a cross sectional view of optical fibers with contoured cross-sectional area, with cladding, and depicts the optical inputs used in previous art and in this invention.

Figure 3 illustrates one preferred embodiment of the present invention.

Figure 4 illustrates another embodiment where the combiner subsystem is an Integrated Optical Combiner.

Figure 5 illustrates an embodiment of the Integrated Optical Combiner Subsystem.

Figure 6 illustrates another embodiment of the integrated Optical Combiner Subsystem.

Figure 7 illustrates still other embodiment of the Integrated Optical Combiner.

Figure 8 illustrates the integrated Optical combiner based on a fiber having multiple rectangular core.

Figure 9 shows an example of the use of optical fiber Y junctions for coherent constructive combination of radiation from four lasers.

Figure 10 shows schematic of the experimentally investigated compound laser system.

Figure 11 shows schematic of compound laser system employing a section of multimode waveguide as Phase Coherent Integrated Optical Combiner.

Figure 12 shows a section of multimode waveguide operating as a interference combiner.

Figure 13 shows schematic of compound laser system for generation a single higher order mode.

The present invention describes a new compound laser system based on constructive superposition of beams generating by individual sources of coherent radiation.

Figure 1 depicts an example of a present state of the art diode laser fiber optic system. Diode lasers 2 are in all array 1. Each diode laser's output passes through lens 3 into a standard optical fiber 4 with circular cross section. The diode laser's output 7, lens 3, and input end of round optical fiber 4 comprise subsystem interface 5. Individual optical fibers 4 continue to a second subsystem interface 8 within combiner subsystem 6. Individual circular cross-sectional fibers are combined into a single circular cross-sectional shape in Figure 1A. Junction 8 has a cross-sectional area comprised of fibers 4 and significant amounts of inter-fiber space 10. Inter-fiber space 10 indicates a loss of power density at

junction 8 as the combiner subsystem's output 11 transfers to delivery subsystem 12.

Figure 2 illustrates two embodiments of the specially-shaped optical waveguide used in the combiner subsystem, having a contoured core 13 and exterior cladding 14. Dimensions of the rectangular fiber core may be, for example, as large as 10 x 200 or 20 x 200 μm in order to match cross sections of the fiber and the diode laser. End faces of the fiber can also be shaped to match also the diode laser's numerical apertures in corresponding directions. This results in efficient coupling between the fiber and the diode laser. Fiber cladding has usually much rounder cross section, resulting from its manufacturing process on a draw tower. Also illustrated is the readily apparent difference between optically connecting diode laser 2 output 7 into a contoured core or a standard round-shaped core.

The fibers having shaped core described here can be drawn from a preform having corresponding shape. It should be emphasized that these fibers are quite different from the fibers with end squashed into elongated cross section proposed in US Patents 4,818,062 and 4,688,884. The fiber drawn from a shaped preform can have the ratio of its core transverse dimensions larger than 1:20, as required to approximate diode laser cross section, while fiber end face can not be squashed to have such large ratio of its principal axes. Moreover, the fiber with shaped core has uniform cross section providing essential conservation of beam brightness and shape over complete fiber length, while the fiber with squashed end has a tapering region changing configuration of the transmitted laser beam. This may be undesirable for some specific applications. For example, in the case when beams from typical diode laser array having rectangular cross sections oriented along the horizontal plane of p-n junction should be recombined in such a way that long axes of all the beams are oriented in the vertical direction, one need a flexible means to transmit and reconfigure a plurality of the beams without changing of brightness and shape of each of the beams.

In addition, the fiber having shaped core possesses an important ability to essentially preserve the state of polarization as the light propagates through the fiber. For example, we have experimentally test a rectangular core fiber excited by a linearly polarized laser diode. The degree of polarization of the light measured at the distal end of the fiber was found to be 0.61. Thus, the flexible Integrated Optical Combiner based on the fibers having shaped core provides unique possibility for pumping of different active media with powerful light beam having certain degree of polarization. The polarization properties of the pump laser beam are potentially very important for diode pumping.

Figure 3 illustrates one preferred embodiment of the present invention with each diode laser 2 in diode laser array 1 emitting into a specially-shaped optical waveguide 13. Subsystem interface 5 may use a lens to reduce the degree of divergence in the highest-divergence axis, the minor axis, from a typical value of 40° to

a value close or the same as the divergence in the low-divergence or major axis, 20°. Subsystem interface 5 may also use waveguides whose input ends are lens-shaped to achieve the same divergence-reduction purpose. Combiner subsystem 16 combines incoming waveguides into a single waveguide. Output port 11 is comprised of an optical waveguide 4 which has a contoured core with cross-sectional shape depending on the number and shape of the input waveguides. For example, 8 input waveguides designed to capture the output of diodes with rectangular cross-sectional shape having a major axis of 200 μm and a minor axis of 10 μm would have a rectangular shaped cross-sectional output port with a major axis of 200 μm and a minor axis of 80 μm . Combiner subsystem's 11 output is fed into delivery subsystem 12 which may use standard round cross-sectional optical fiber as illustrated in figure 3B, or may use contoured optical waveguides whose core has major and minor axes approximating those of the combiner subsystem's output and having a means to mutually match corresponding numerical apertures.

Figure 4 illustrates another preferred embodiment of the present invention where diode laser array 1 is matched to combiner subsystem 16 that is a discrete unitized component called an Integrated Optical Combiner. Each diode laser 2 in diode laser array 1 is aligned with one Integrated Optical Combiner input port 23. Integrated Optical Combiner input ports 23 are contoured. Integrated Optical Combiner Subsystem 16 combines multiple input port 23 to one output port 24, whose cross sectional shape is approximately square or rectangular, depending on the number and shape of input ports 23. Output port 24 is optically connected to delivery subsystem input port 29, comprised of a standard round optical fiber or a single ellipsoidal shaped optical waveguide whose major and minor axes approximate those of output port 24.

Figure 5 illustrates one preferred embodiment of Integrated Optical Combiner 18, where input ports 23 of optical waveguides 27 are contoured in cross-sectional shape. Input ports 23 are staggered or stair-stepped, such that in viewing input port side 25 of Integrated Optical Combiner 18 each rectangularly-shaped input port has its major and minor axes parallel to the major and minor axes, respectively, of input port side 25, and each successive input port going from left to right has its bottom flat edge slightly above the previous port's top flat edge as shown in figure 5a. A left-most input port is located near the bottom left corner of input port side 25 of Integrated Optical Combiner 18, and a right most input port is located near the top right corner of input port side 25 of Integrated Optical Combiner 18. Output port 24 is located on the opposite side of Integrated Optical Combiner 18 as input ports 23. Output port 24 has its major and minor axes parallel to the major and minor axes, respectively, of output side 26. Output port 24 has an approximately square-shaped core or a rectangularly-shaped core, depending on the number and shape of input ports 23, shown in figure 5b. Integrated

Optical Combiner 18 is an enclosure molded, formed, built up, layered, or otherwise manufactured to provide internal channels and chambers that perform the functions of the combiner subsystem. Cores 27 in Integrated Optical Combiner 18 can be laid in, layered in, forced in, molded in, built up, poured in, clamped in, or otherwise set and held in place during the manufacturing process.

Figure 6 illustrates another preferred embodiment of Integrated Optical Combiner 18 where input ports 23 have their cross-sectional major and minor axes rotated relative to the major and minor axes of input port side 25 of Integrated Optical Combiner 18. The rotation allows the internal channels and chambers of the Integrated Optical Combiner to be manufactured using cutting or molding technologies in upper body 20 and lower body 21 of Integrated Optical Combiner 18. Output port 24 may also have its major and minor axes rotated relative to the major and minor axes of output port side 18. See also figures 6A, 6B and 6C. Upper body 20 and lower body 21 can be clamped, heated, glued, or otherwise forced or held together during manufacturing.

A preferred embodiment for a set of diode lasers when an Integrated Optical Combiner like that illustrated in Figure 6 is used is to rotate the major and minor axes of the individual laser diodes so that their output shape rotates the same amount as the axes rotation of the input ports in the Integrated Optical Combiner. This embodiment may also allow the diode lasers to be more tightly packaged than non-rotated arrays.

Another preferred embodiment of an Integrated Optical Combiner has both axes of the input ports parallel to the major and minor axes of the Integrated Optical Combiner's input port side. The input ports are stepped in an up and down fashion going from left to right along input port side. The stepping allows an Integrated Optical Combiner's height to be no more than a specified number of input ports high by adding more ports along the input port side's major axis. The output port will have a contoured core whose shape is a result of combining differing numbers of input ports with differing major and minor axes.

Figure 7 illustrates still another preferred embodiment of Integrated Optical Combiner which comprises at least one optical fiber having one flat side surface and one side surface of such a shape that the light irradiated by each diode laser through said flat side surface is reflected and focused by said shaped side surface in the direction parallel to the axis of said fiber collecting the light from all said diode lasers.

Figure 8a shows a schematic of another Integrated Optical Combiner employing special having multiple rectangular core. All optical fiber 81 has a plurality of cores 82 having rectangular cross sections. The number of these cores is equal to the number of active regions of laser diode array 83. It typical case it is equal to 12. Fiber 81 has cladding 84 which is side removed in the region 85 where laser diode array 83 is butt-joined to fiber 81. To remove the cladding from one side of the fiber, one can , for example, polish the fiber in a special

glass block. Laser diode array 83 should be butt-joined to the fiber 81 under some angle to the fiber axis to ensure effective overlapping of each active element of the array with cross section of the corresponding fiber core. This provides effective coupling of light from diode array into the fiber cores. Each fiber core has a means to reflect the side coupled light in the direction along the fiber axis. Appropriate incisions 86 made in the fiber cores 82 can be used for reflection of the light irradiated by laser diode 87, as shown in Fig. 8b. These incisions can be fabricated, for example, with the help of focused beam of CO₂ laser, excimer laser or other micro-machining techniques.

The preferred embodiments show the advantages in using this inventions' solutions instead of previous implementations. The interfaces to the combiner subsystem have been improved through the creation and use of input ports whose cross-sectional shape and major and minor axes are close to the cross-sectional shape and major and minor axes of the components with which they interface and having means to match numerical apertures of the input ports and the components. In the case of a set of diode lasers, each diode laser is matched to a combiner subsystem intake port whose cross-sectional shape is appropriately contoured to have the major and minor axes dimensions not smaller than that of the output of the laser. In addition to creating an efficient interface, it may eliminate the need for the lenses used in previous systems when the input ends of the contoured waveguide is shaped so as to reduce the beam divergence in the diode laser's highest-divergence axis (the minor axis) to that of the low-divergence axis (the major axis). At the output side of the combiner subsystem, the output port has a cross-sectional shape approximately that of a square or of a rectangle, depending on the number of laser diodes and characteristic output shape of each diode. The input port's shape of the delivery subsystem may be designed to closely match the combiner subsystem's output port shape. This may be a standard circular cross-sectional shaped core or may be a special contoured core.

A calculation can be made of the potential efficiency gain between this invention and the previous art. The comparison is made between the current invention's matching of a typical diode laser's output shape of 200 μm by 10 μm, coupled with the use of a divergence-reducing lens or lens-shaped fiber ends, relative to the previous art using an optical fiber whose core was circular in cross section and whose diameter was 200 μm. The power densities of both systems at an equal distance into the combiner subsystem from the point of issue would be related to each other as:

$$(200^2 (\pi/4)) / (200(10)) = 15.7$$

This shows that the current invention can easily deliver power densities over all order of magnitude higher using the same diode laser source.

Additionally, this invention discloses an Integrated Optical Combiner, a discrete component which is the combiner subsystem of a diode laser array power delivery system. The Integrated Optical Combiner allows significant savings in manufacturing to be realized over previous art by reducing the discrete component count on each board, increases ease of manufacturing, and increases reliability by reducing the component count in the entire system.

The laser diode sources of radiation considered above in detail are only one example of active elements that can be employed in high power compound laser system based on superposition of beams generated by a number of coherent sources. Any active elements generating coherent radiation can generally be employed in the compound laser system. For example, this system can use active fiber lasers or amplifiers as active elements. Optical parametric amplifiers or oscillators based on frequency conversion in nonlinear material pumped with an external laser beam can also be employed as the active elements of the compound laser system.

Special Phase Coherent Integrated Optical Combiner is a key component of the high power compound laser system. Its main function is to provide constructive superposition of coherent beams generated by all active elements of the compound laser system.

One preferred embodiment of the system is shown in Figure 9. Light beams from four individual active elements 91 are coupled into single-mode fibers with polarization rotators 92 and phase modulators 93. The fibers are spliced together with the help of Y-junctions providing their cascade connection. Each active element 91 has an internal means of optical feedback. In the case of lasers used as active elements, rear mirror or Bragg reflector of the laser can provide the means of internal optical feedback. In the case of optical parametric oscillator based on counter-propagating signal and idler waves, coupling between these signal and idler waves can provide the means of internal feedback.

Output fiber has a means of external optical feedback which can be provided by a reflecting coating of the fiber facet, a mirror or a Bragg reflector. Feedback in the system ensure coherent adding of the radiation in compound laser system comprising of four active elements 91.

The laser system operates as follows. The radiation reflected from exit mirror 95 passes through cascaded Y-junctions, uniformly distributes among the active elements 91, amplifiers under double path through them and returns to the inputs of Y-junctions. Let I_1 and I_2 are the intensities of radiation arriving at the inputs of each of Y-junction and let $\Delta\phi$ is the phase difference between them. The intensity at the output of Y-junction is

$$I = (I_1 + I_2 + 2(I_1 I_2)^{1/2} \cos \Delta\phi) / 2 \quad (1)$$

The output intensity reaches its maximum value when the following two conditions are satisfied: $I_1 = I_2$ and

$\Delta\phi = 0$. This case corresponds to summation of the radiation intensities in Y-junction without any losses. If similar conditions are satisfied by all Y-junctions, this results in the minimum value of the lasing threshold of the system. However, if incoherent radiation reaches the inputs of the Y-junctions, then the power losses in each of them amount to 3 dB, and this regime of operation of the laser system is characterized by a much higher threshold. The first condition of equality of the intensities can be satisfied by suitable pumping of the individual active elements. However, the second condition, $\Delta\phi = 0$, can be satisfied only if, first, the radiation in the various arms of the system is mutually coherent and, second, if the optical path difference between these arms is a multiple of an integer number of wavelength. The last condition can be satisfied by tuning phase modulators 93 in each arm or by choosing very different optical lengths of the arms because the longitudinal modes are then selected in the laser system and the radiation with required wavelength is generated automatically.

The proposed approach can be used, in particular, to add the powers of individual semiconductor laser diodes and of several fiber lasers having separate pump sources. As a result, the output radiation is concentrated in a single output fiber, which makes it most convenient for any further use.

In a model experiment we used an all-fiber laser system shown in Fig. 10. The system comprised of two separate active fibers A and B doped with Nd^{3+} in a relative concentration of 10^{-3} . These fibers are single-mode at the lasing wavelength of $1.08 \mu\text{m}$. They are connected by an X-type junction formed from sections of the two fibers (polished down to the core) which could be moved relative to one another by a micro-positioner. The use of such a junction avoided completely the optical losses in the coupling region and enabled us to alter the coefficient representing the division by the junction. We were also able to record the power of the uncompensated radiation P_s at free output of the junction (in the case of Y-junction such radiation would have been scattered at the output). The three other arms (channels) of the junction were brought into contact with dielectric mirrors 101 whose reflection coefficients at the lasing wavelength were 95%. The length of the active arm A of the system was 0.9 m and the length of the arm B was 1 m. This ensured a practically complete absorption of the radiation from an Ar laser (having wavelength $\lambda = 514 \text{ nm}$) which was used as a pump and the difference between the arm lengths was sufficient to satisfy automatically the phase relationships governing lasing in the system. The output part of the fiber shared by both arms was about of 25 cm long. The active fibers were excited through their ends. Each arm of the laser system was pumped independently and the pump power could reach 20 mW in each arm. Two fiber polarization controllers were used to achieve maximum constructive (in the shared output arm of the X-junction) or destructive (in the free arm of the junction) interference.

The experiment has demonstrated 95% efficiency of radiation power addition in the system.

Cascaded Y-junctions shown in Figure 9 are not the only possible embodiment of the Phase Coherent Integrated Optical Combiner. Many of the Integrated Optical Combiners described above can be employed in the Phase Coherent Integrated Optical Combiner, if appropriate external feedback is provided. It is essential for operation of the compound laser system to provide efficient coupling between laser and light delivering waveguide in both directions. This is important condition for establishing external feedback required for operation of the system. This point becomes really critical in the case of the coupling between diode lasers and fibers as a result of the difference in their geometries. It seems that Integrated Optical Combiner based on fibers having shaped core described above in detail offers a unique solution of the problem.

An additional preferred embodiment of the compound laser system employing the Phase Coherent Integrated Optical Combiner based on a section of a multimode waveguide operating as an interference combiner is shown in Figure 11. Light from four active elements 111 is delivered by waveguides 112 to Phase Coherent Integrated Optical Combiner 113 performing adding of powers of the individual incoming beams and coupling the light into output waveguide 114. Mirror 115 provides an external feedback in the system.

Operation of the section of multimode waveguide as an interference beam combiner is illustrated in Figure 12. It is known that section of multimode waveguide whose width W is large enough to support many lateral modes can operate as a beam splitter. Self-images of the waveguide input occur in planes at distance L from the input in which the accumulated phase difference between excited modes are multiples of 2π . Multiple self-images are formed at intermediate planes. If the length of multimode waveguide section is equal to $L/8n$, then an input beam which is central fed is nearly uniformly split among n output waveguides. Back propagation of appropriately phased n input beams results in coherent combining their powers in one output beam. Feedback means 115 shown in Figure 11 provides conditions for automatically phasing of all the beams required for operation of Phase Coherent Integrated Optical Combiner.

For some practical applications it is desirable to have a compound laser system generating a powerful output beam corresponding a higher order mode of the multimode waveguide. Such compound laser system is shown in Figure 13. In this case the section of multimode waveguide should not have a specific length. Input beams having appropriate relative phases excite an output beam corresponding to higher order mode 134 in the multimode waveguide. Feedback means 135 automatically provides required phase relations between all input beams.

Different types of optical waveguides can be employed in the Phase Coherent Integrated Optical

Combiner described above. In one preferred embodiment one can design this Combiner based on integrated optical rib waveguides connected to a section of planar multimode waveguide being fabricated on the same substrate. A section of multimode optical fiber can also be used in such a Combiner. Another preferred embodiment used a section of a multimode optical fiber having rectangular cross section. For using this fiber in combination with single-mode light delivering input/output fibers, it may be convenient to use the rectangular fiber core of such size that the rectangular core fiber is single mode in one direction and multimode in another direction.

Having described preferred embodiments of the invention with reference to the accompanying drawings, it is to be understood that the invention is not limited to the precise embodiments, and that various changes and modifications may be effected therein by skilled in the art without departing from the scope or spirit of the invention as defined in the appended claims.

Claims

1. A compound laser system having at least two active elements including lasers or optical amplifiers, enhancing the power of optical beam, and having at least one means of internal optical feedback, characterized by the active elements having means of optical connection of said optical beams to a phase-coherent combiner; the combiner performing constructive superposition of the optical beams to add their intensities, and the combiner having a means of external optical feedback providing feedback for all the active elements.
2. A laser system according to claim 1, further characterized in that the active elements are optical parametric amplifiers based on frequency conversion in a nonlinear medium pumped with all external source; the means of internal optical feedback includes at least one mirror or Bragg reflector inside or at the surface of a nonlinear medium of the optical amplifiers or is provided by coupling between signal and idler waves in the nonlinear medium for the case of counter-propagating wave configuration of the optical parametric amplifiers.
3. A laser system according to claims 1 or 2, further characterized by having the means of optical connection and the phase-coherent combiner be integrated optical waveguides fabricated on a common substrate, where the integrated optical combiner includes cascaded Y-junctions having a single output or a section of multimode optical waveguide; and the means of external feedback is a mirror or Bragg reflector at the output of the combiner.
4. A laser system according to claims 1, 2 or 3, further characterized by having the active elements be

semiconductor lasers, integrated optical micro-lasers or amplifiers, or optical fiber lasers or amplifiers.

5. A compound laser system according to claim 1, further characterized by having the active elements be a diode laser array, the means of internal feedback are mirrors of each individual laser of the diode laser array, the means of optical connection are optical fibers with each having an essentially rectangular input cross section of its core and with each being able to transmit polarized light, the optical combiner is phase-coherent and is a cascaded Y-junction of the optical fibers or a section of multi-mode optical fiber having an essentially rectangular core cross section, and the Y-junction has an output fiber with an essentially round core cross section.
6. A flexible compound laser system characterized by having a diode laser subsystem with at least two diode lasers or an array of diode lasers whose output is non-circular in shape, a means of optical connection from the diode laser subsystem to an optical combiner being a set of optical waveguides with each diode laser having its output captured by an optical waveguide, each optical waveguide having a core cross section that is contoured in shape matching the cross section of a beam irradiated by the diode lasers and having means to match its numerical aperture to that of the diode laser, the optical combiner combining individual beams of captured diode laser light from the optical waveguides into a single output which has a geometry that is substantially a superimposition of the input waveguides causing the output to substantially maintain or increase an initial input power density, and a means for delivering said output.
7. A laser system according to claim 6, further characterized by having the means of delivering the system's output be a delivery subsystem with an input port which is an optical waveguide whose cross-sectional core shape is a standard round shape or is contoured with or without a lens between the output port and the delivery subsystem input port with or without a specially-shaped end on the delivery subsystem input such that any divergence in the combiner subsystem emitted output is equalized between the combiner subsystem output's major and minor axes and by having the means to match the numerical apertures of the optical waveguides in the optical combiner to that of the diode laser be input ports of the optical waveguides with shaped ends or lenses.
8. A laser system according to claims 6 or 7, in which the optical combiner subsystem is further characterized by being an integrated single component, an Integrated Optical Combiner, with a body having

channels and voids with optical waveguide material in the channels and voids and with input ports and an output port where the optical waveguide material in each input port has a core cross-sectional shape substantially matching the output shape of the laser diodes and where optical waveguide material in the output port has a cross-sectional shape contoured to be substantially geometrically equivalent to a superimposition of said input ports so that the beams at the output port substantially maintains an initial input power density, and where the input ports of the Integrated Optical Combiner are arranged so that each port is substantially aligned with a corresponding diode laser output whether or not the individual diode lasers are linearly arranged or rotated about the major axis of each diode laser.

9. A laser system of claims 6 or 7, where the optical combiner is further characterized by having its optical waveguides be individual optical fibers which are combined by a cascade-like arrangement of optical combiners.
10. A laser system according to claim 8 where the Integrated Optical Combiner is further characterized by having one or more optical fibers with a complex shape such that there is at least one flat side surface and one side surface of such a shape that light irradiated by each diode laser passing through the flat side surface is reflected by the shaped side surface in the direction of the axis of the fiber collecting the light from all the diode lasers which overlap with the complex fiber.
11. A laser system according to claim 8, where the Integrated Optical Combiner is characterized by having at least one multi-core optical fiber with a low index cladding surrounding at least two cores where each core has a rectangular cross section and a diode laser array having at least two individual diode lasers to which the multi-core fiber is butt-joined after removing the cladding from one side of the fiber in a region of the butt-joining so that light beams irradiated by each individual diode laser are coupled into a corresponding core of the multi-core fiber and each of the multi-core fiber cores has a means to reflect the beams in the direction along a longitudinal axis of the multi-core fiber.

FIG. 1

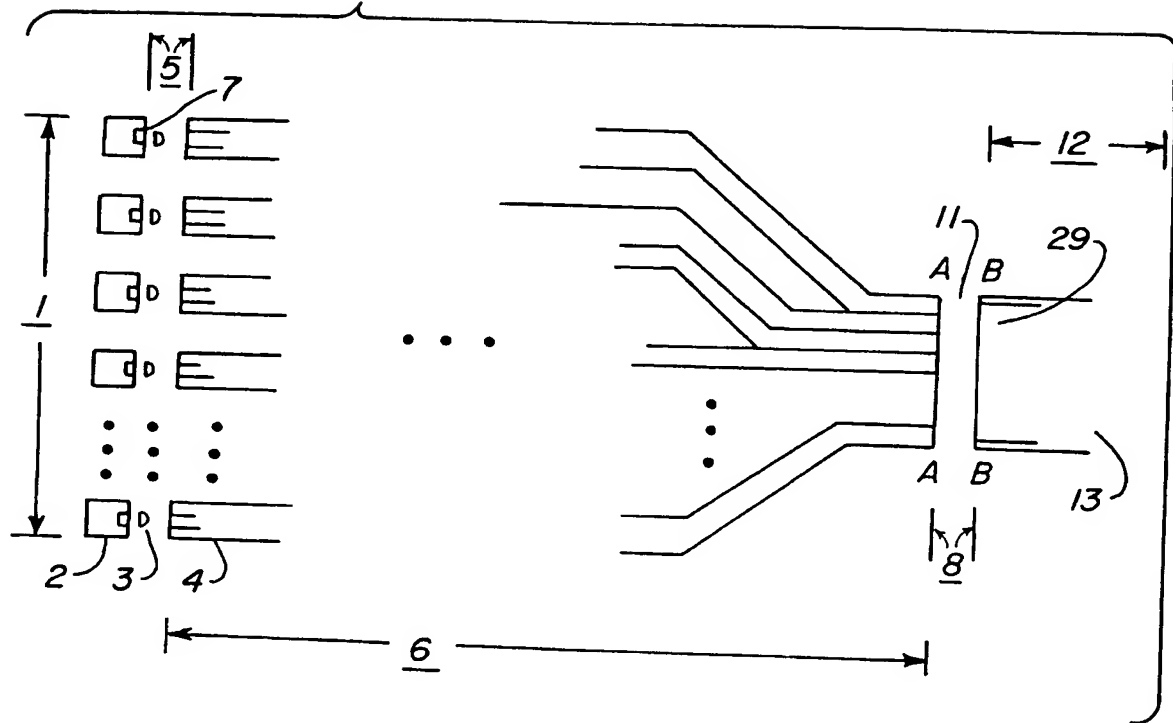


FIG. 1A

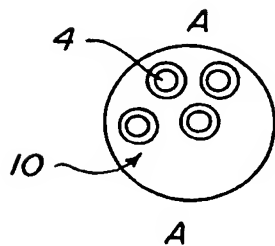


FIG. 1B

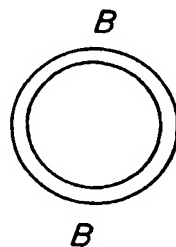


FIG. 2

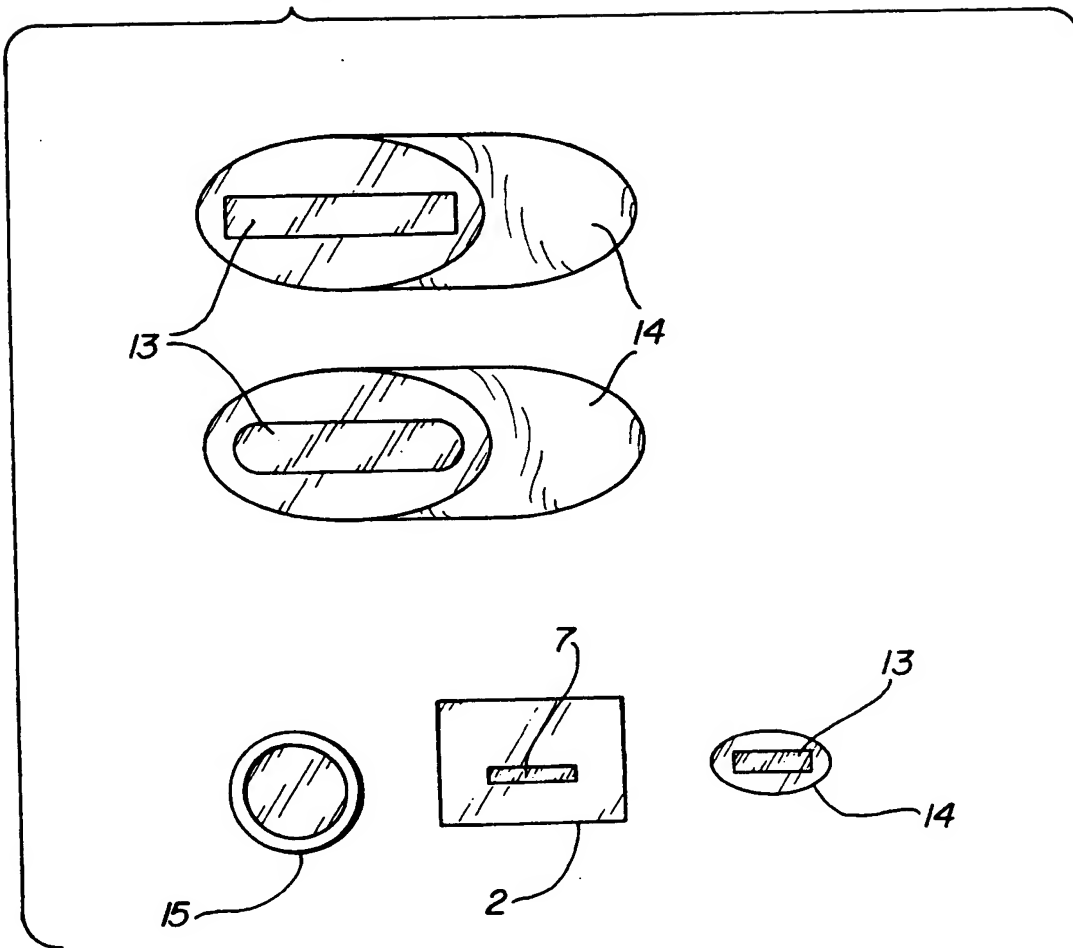


FIG. 3

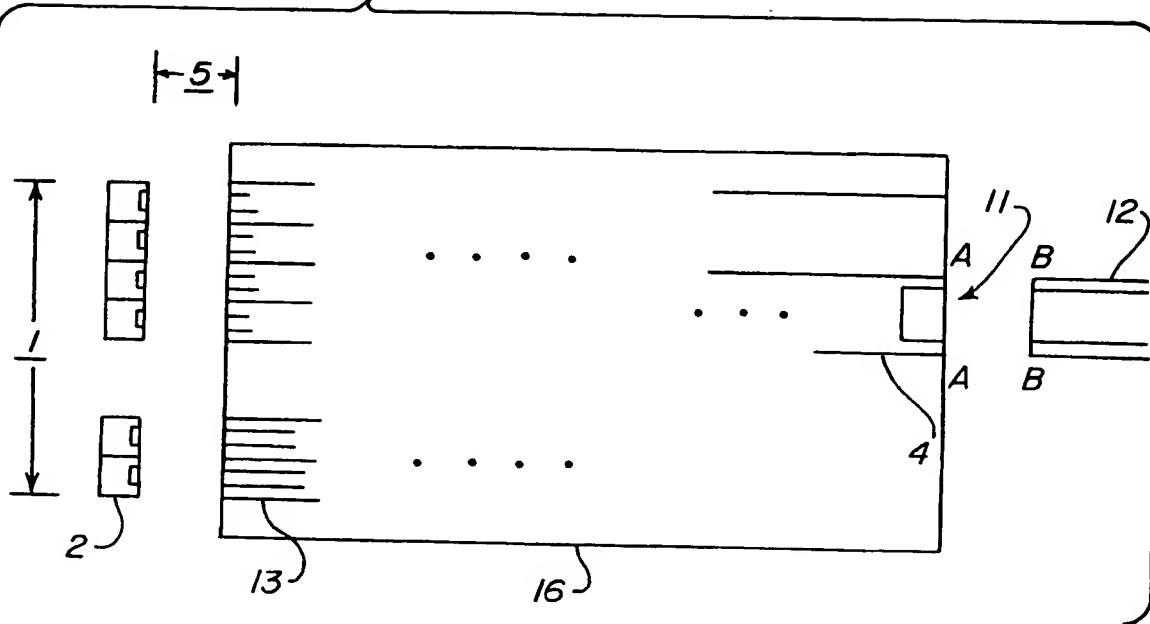


FIG. 3A

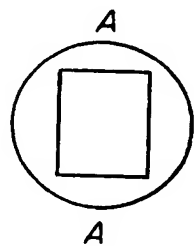


FIG. 3B

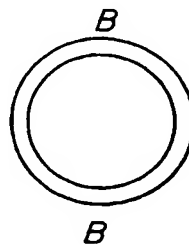


FIG. 4

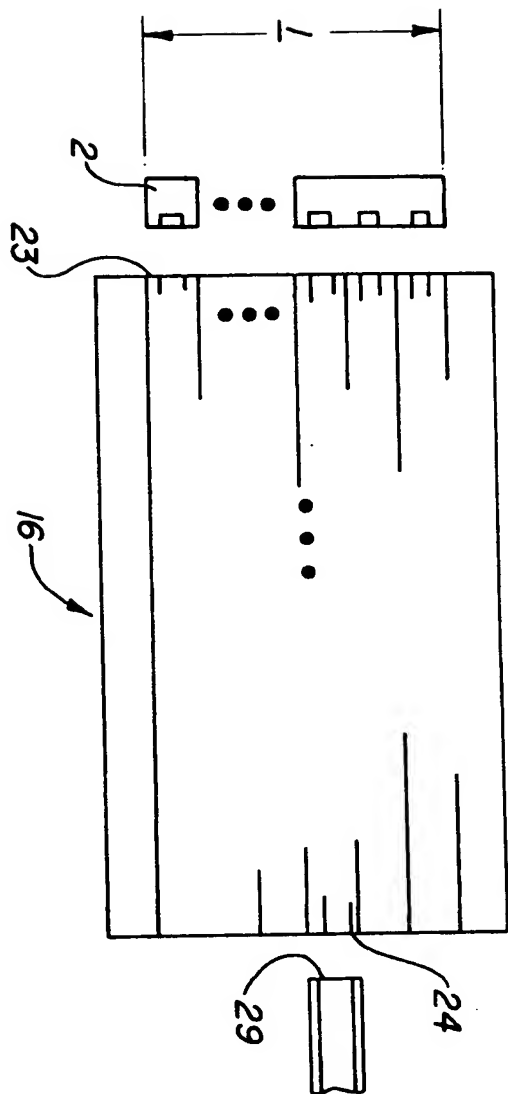


FIG. 5

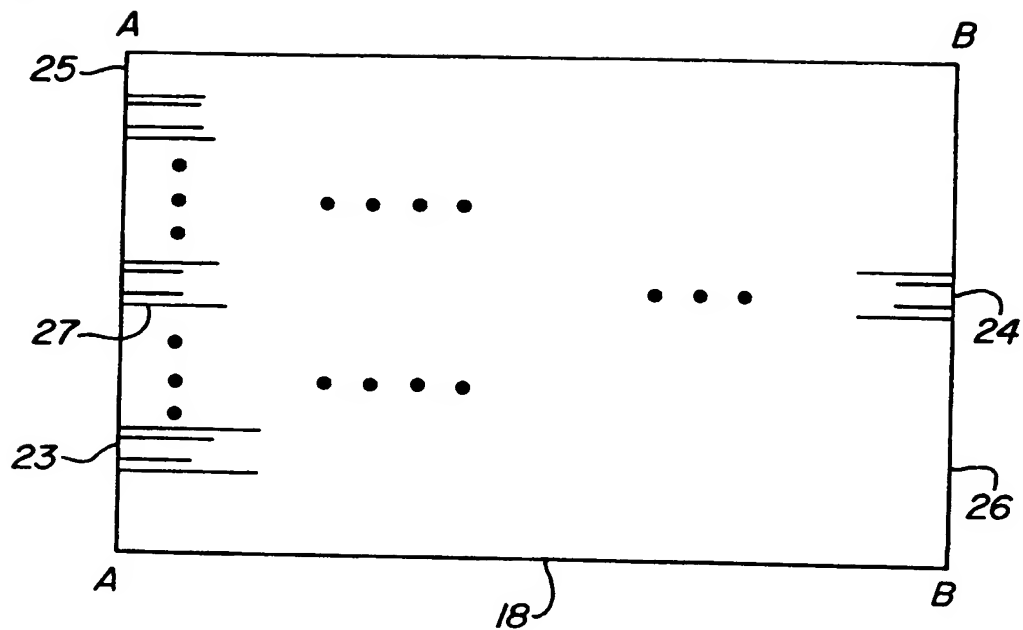


FIG. 5A

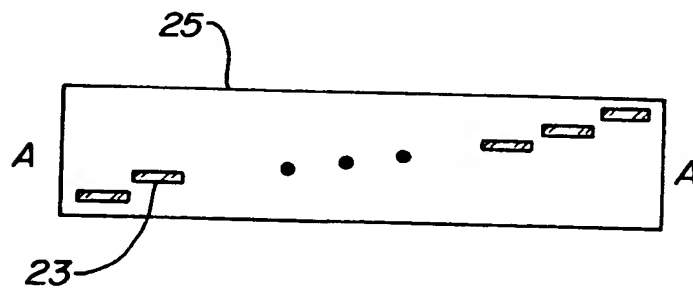


FIG. 5B

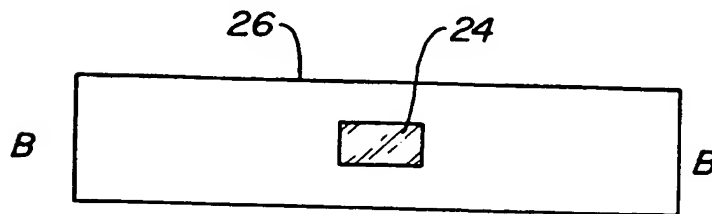


FIG. 6

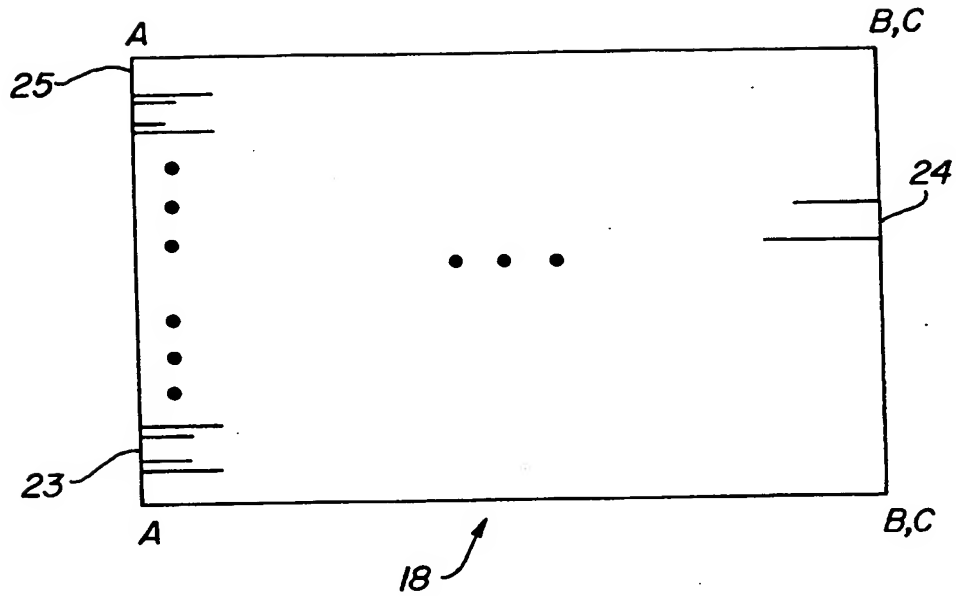


FIG. 6A

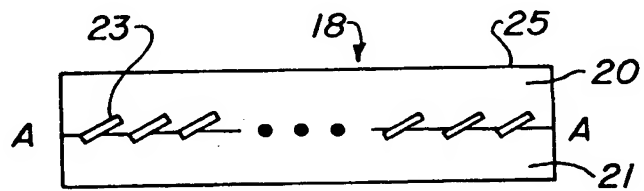


FIG. 6B

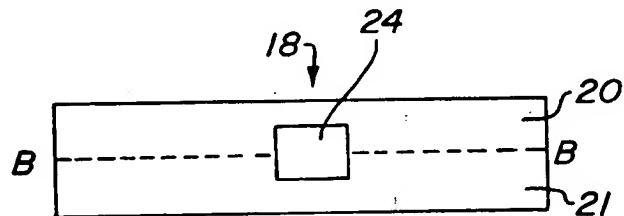


FIG. 6C

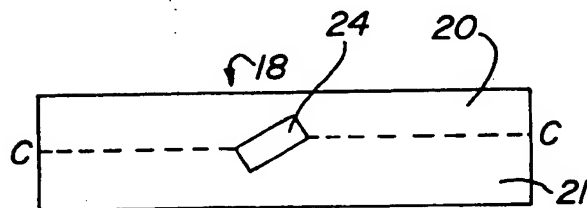


FIG. 7

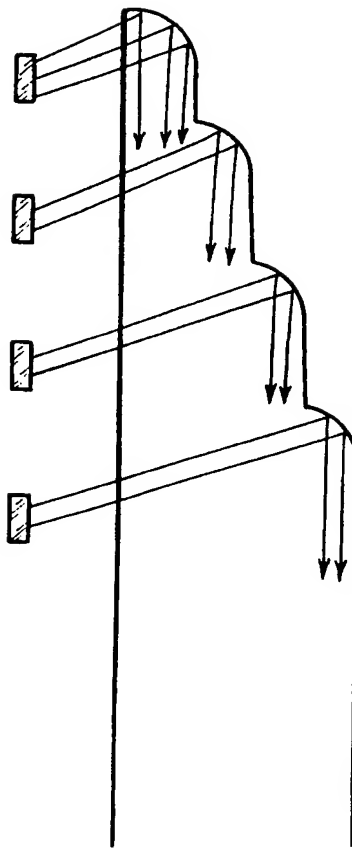


FIG. 8

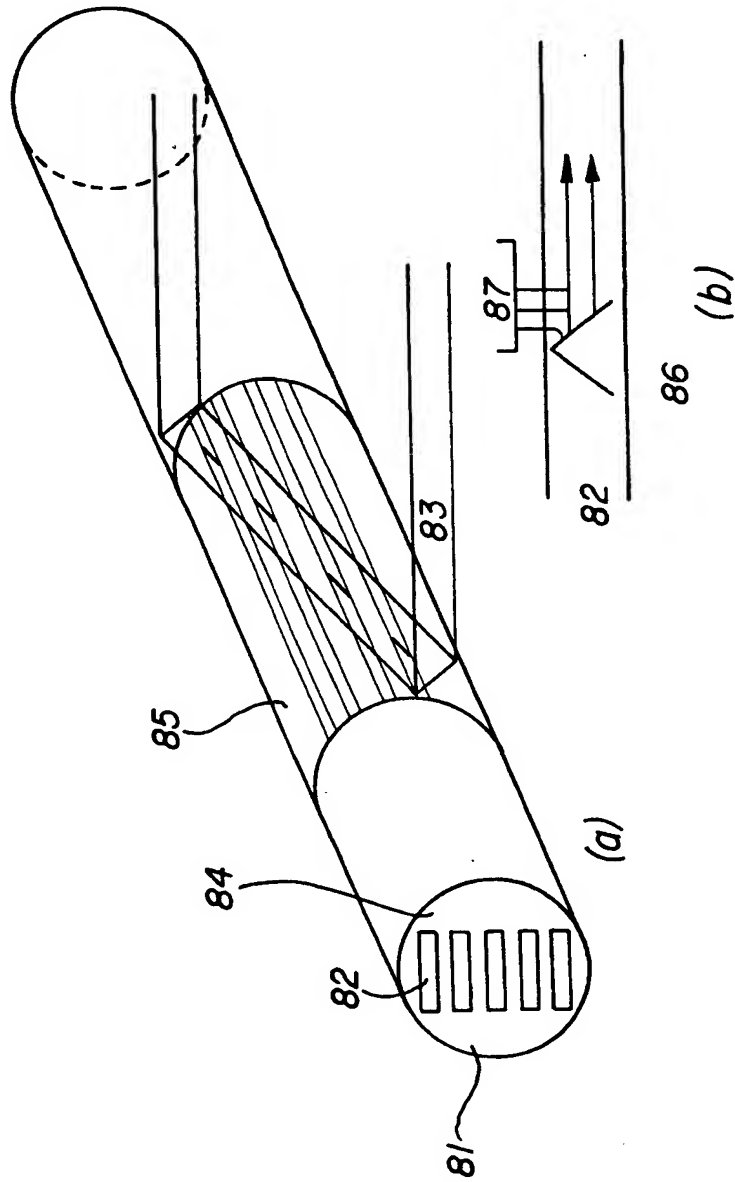


FIG. 9

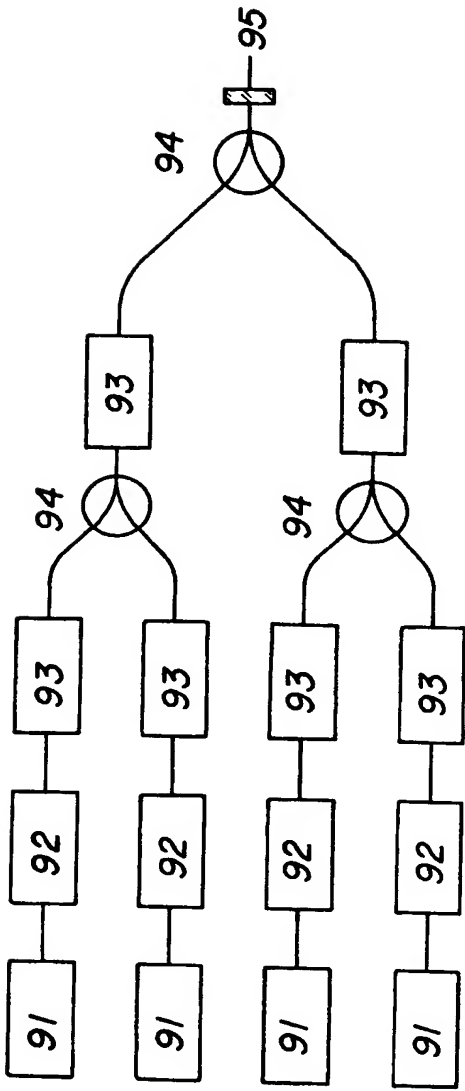


FIG.10

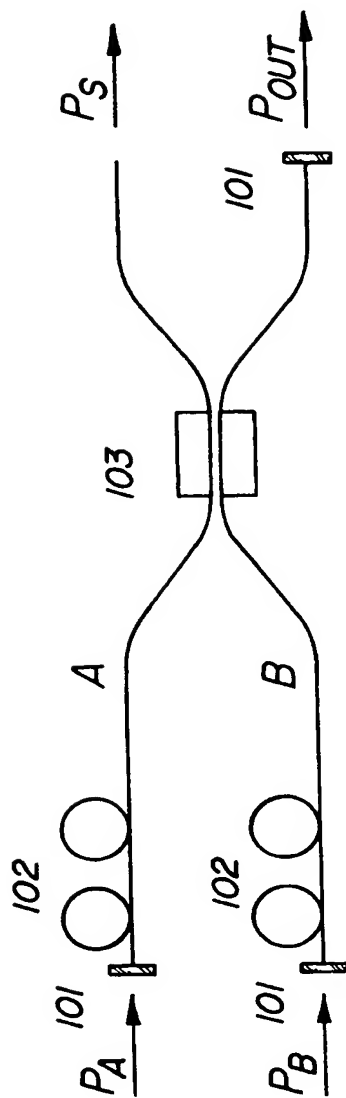


FIG. 11

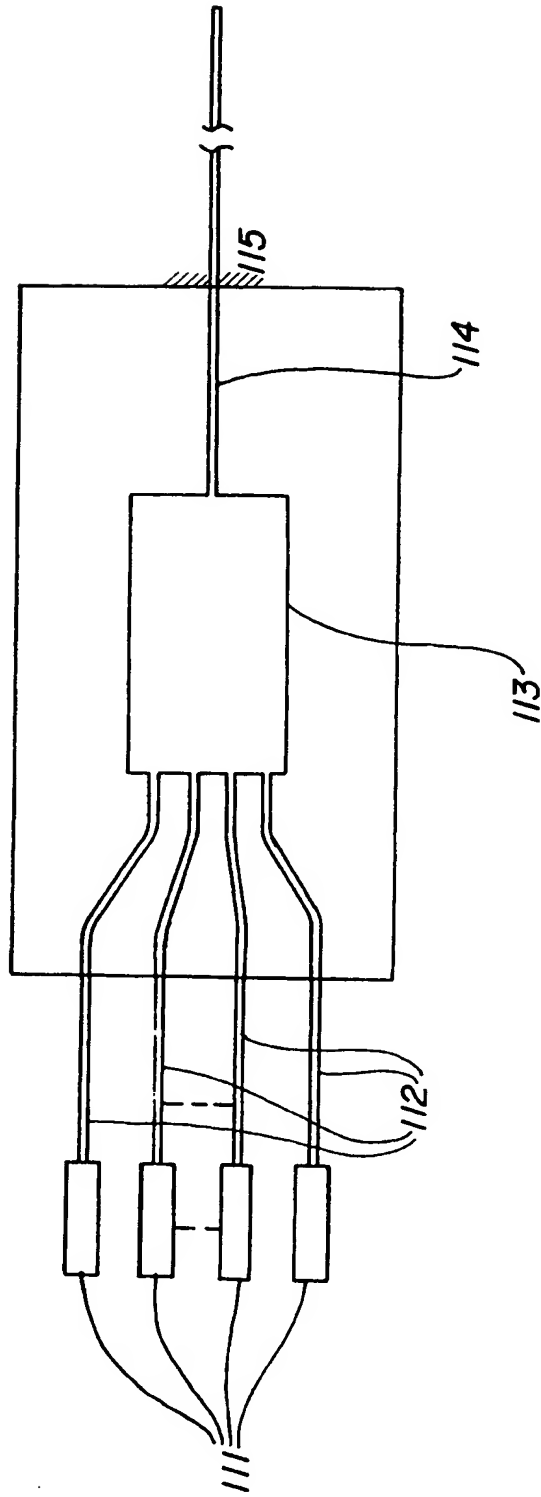


FIG.12

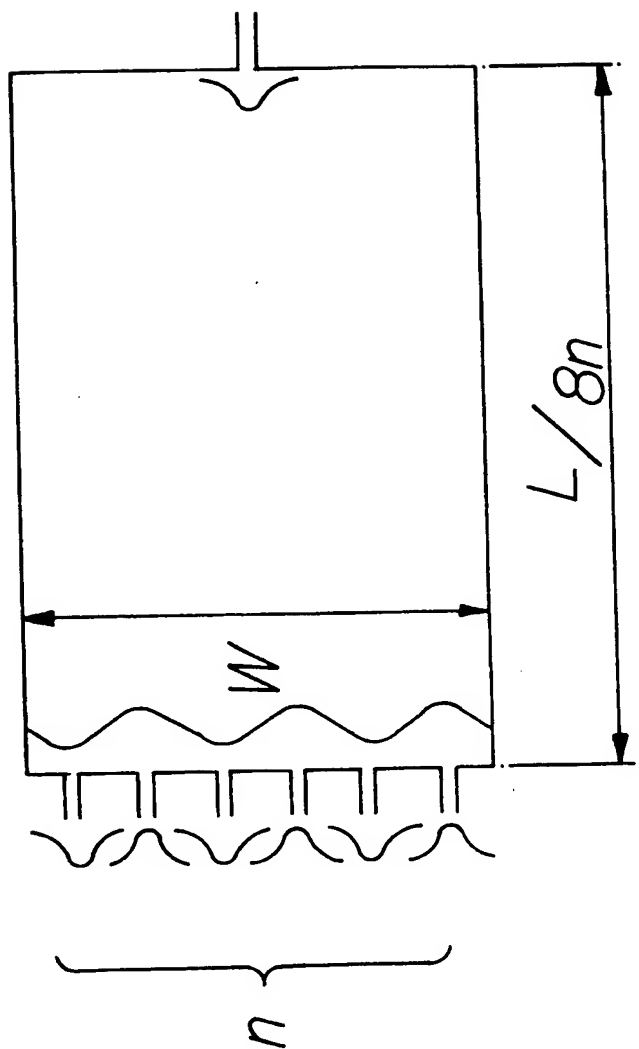
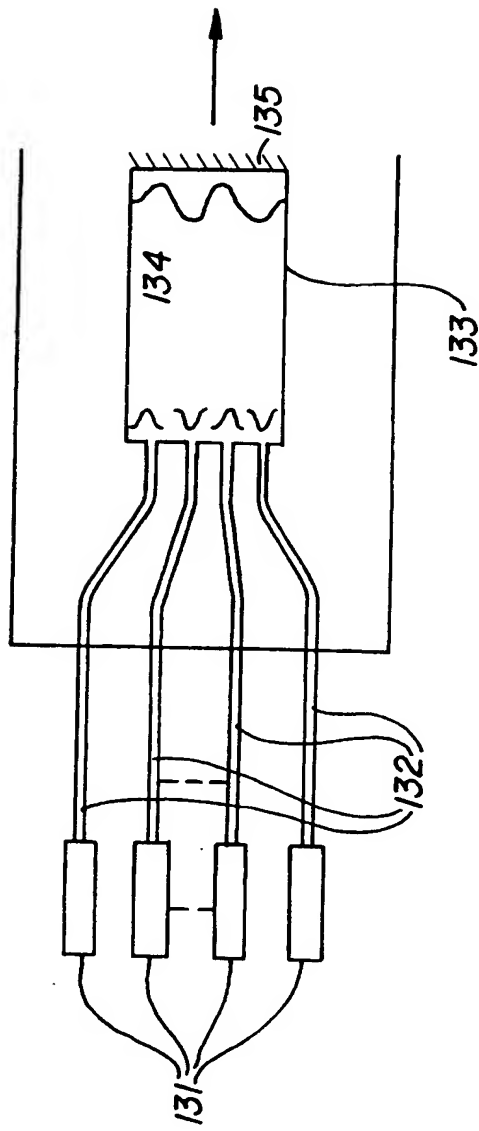


FIG. 13



(19)



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(54) Compound laser system for high power density

(57) The present invention provides compound laser system for generating beams of high brightness and high power density by constructive phase coherent combination of the beams generated by a number of individual sources of coherent radiation. In one preferred embodiment, it provides a system for the delivery of high powered output from a set of inexpensive, comparatively low-powered diode lasers and comprises three subsystems: a diode laser subsystem which is the source of power for the system; a combiner subsystem which combines the output of the diode lasers; and, an optional delivery subsystem which may be needed to deliver the combined output to its desired destination for industrial or medical applications.

The combiner subsystem may be implemented in its entirety as an Integrated Optical Combiner, a single component, performing all the combiner subsystem's functions. Different preferred embodiments of Phase Coherent Integrated Optical Combiners are proposed. One of them employs an optical fiber having a shaped core to provide efficient matching to the geometry of typical laser diodes. Each diode laser's output of a diode laser array is captured by a single optical fiber with a core whose cross-sectional shape is contoured so that major and minor axes of a laser diode's output shape are not larger than major and minor axes of an optical waveguide and whose numerical apertures are closely matched to the numerical apertures in the directions of corresponding axes.

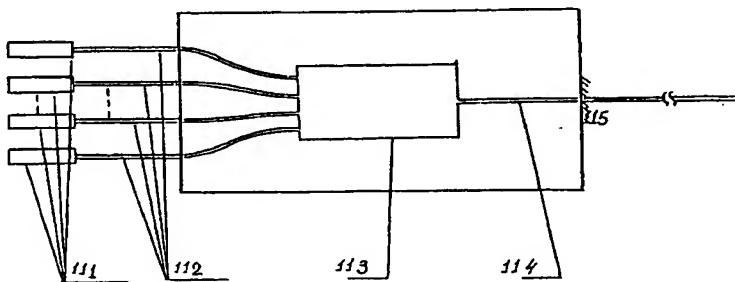


Fig. 11

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EUROPEAN SEARCH REPORT

Application Number
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DOCUMENTS CONSIDERED TO BE RELEVANT			
Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int.Cl.6)
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A	* the whole document *	3,5	
X	WO-A-91 01056 (AUSTRALIAN ELECTRO OPTICS) 24 January 1991 * abstract; figure 2 *	1,4	
X	OPTICS LETTERS, vol. 18, no. 18, 15 September 1993, pages 1520-1522, XP000396929 MOREL J ET AL: "COHERENT COUPLING OF AN ARRAY OF ND3+-DOPED SINGLE-MODE FIBER LASERS BY USE OF AN INTRACAVITY PHASE GRATING" * figure 3 *	1,4	
A	EP-A-0 501 751 (NIPPON ELECTRIC CO) 2 September 1992 * abstract; figure 1 *	3	
A	US-A-5 351 323 (MILLER WILLIAM J ET AL) 27 September 1994 * figures 4-6 *	1,5	TECHNICAL FIELDS SEARCHED (Int.Cl.6)
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This procedure does not apply to documents cited for other reasons			
Place of search THE HAGUE		Date of completion of the search 4 April 1996	Examiner CLAESSEN, L
<p>CATEGORY OF CITED DOCUMENTS</p> <p>X : particularly relevant if taken alone Y : particularly relevant if combined with another document of the same category A : technological background O : non-written disclosure P : intermediate document</p> <p>T : theory or principle underlying the invention E : earlier patent document, but published on, or after the filing date D : document cited in the application L : document cited for other reasons & : member of the same patent family, corresponding document</p>			



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Application Number
EP 95 20 3574

DOCUMENTS CONSIDERED TO BE RELEVANT			
Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int.Cl.6)
A	IEEE PHOTONICS TECHNOLOGY LETTERS, vol. 6, no. 4, NEW YORK US, pages 531-533, XP000446616 H. YAMADA ET AL: "Mode shape convertor produced by the thermal diffusion of different dopants" * the whole document * -----	1,5	
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<p>The present search report has been drawn up for all claims</p>			
Place of search		Date of completion of the search	Examiner
THE HAGUE		4 April 1996	CLAESSEN, L
CATEGORY OF CITED DOCUMENTS X : particularly relevant if taken alone Y : particularly relevant if combined with another document of the same category A : technological background O : non-written disclosure P : intermediate document T : theory or principle underlying the invention E : earlier patent document, but published on, or after the filing date D : document cited in the application L : document cited for other reasons ----- & : member of the same patent family, corresponding document			

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CLAIMS INCURRING FEES

The present European patent application comprised at the time of filing more than ten claims.

- ☐ All claims fees have been paid within the prescribed time limit. The present European search report has been drawn up for all claims.
- ☐ Only part of the claims fees have been paid within the prescribed time limit. The present European search report has been drawn up for the first ten claims and for those claims for which claims fees have been paid, namely claims:
- ☐ No claims fees have been paid within the prescribed time limit. The present European search report has been drawn up for the first ten claims.

LACK OF UNITY OF INVENTION

The Search Division considers that the present European patent application does not comply with the requirement of unity of invention and relates to several inventions or groups of inventions, namely:

see sheet B

- ☐ All further search fees have been paid within the fixed time limit. The present European search report has been drawn up for all claims.
- ☐ Only part of the further search fees have been paid within the fixed time limit. The present European search report has been drawn up for those parts of the European patent application which relate to the inventions in respect of which search fees have been paid, namely claims:
- ☒ None of the further search fees has been paid within the fixed time limit. The present European search report has been drawn up for those parts of the European patent application which relate to the invention first mentioned in the claims, namely claims: 1-5



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EP 95 20 3574 -B-

LACK OF UNITY OF INVENTION

The Search Division considers that the present European patent application does not comply with the requirement of unity of invention and relates to several inventions or groups of inventions, namely:

1. Claims 1-5 : A compound laser system incorporating a phase coherent combiner using external feedback.
2. Claims 6-11 : A compound laser system incorporating waveguides with special cross section to match the numerical apertures of laser and receiver.

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